Space Vector Based Hysteresis Control Strategy with Fixed Switching Frequency for UPQC

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Abstract

A space vector based hysteresis control strategy with fixed switching frequency for Unified Power Quality Conditioner (UPQC) is proposed. This method researches the hysteresis control strategy with fixed switching frequency. On this basis, it combines the hysteresis control strategy with fixed switching frequency and space vector control by the conversion of the filter hysteresis tracking control. In the final control strategy, it judges the region of command voltage vector by using the sign of phase-to-phase current error vector . Compared with the traditional current tracking algorithm, detection of three-phase grid voltage is not needed and the algorithm is optimized. The control strategy can solve the problem that switch frequency is unstable and overcome the problem of interphase interference in three-phase three-wire system. Through the MATLAB/Simulink simulation, proved that this kind of control strategy for Unified Power Quality Conditioner proposed in this paper is feasible and effective.

Keywords

United Power Quality Conditioner; Hysteresis Control with Fixed Switching Frequency; Space Vector; Interphase Interference

Introduction

In recent years, with the continuous development of electric power industry, the power quality problems get more and more attention . With the using of a large number of non-linear loads and impact loads, the power quality is deteriorating and the user has suffered a great loss [Akagi H., 2002] [Enslin J H R, 2004] [Oliva A R, 2004] [Papathanassiou S A, 2005].

As a power quality comprehensive compensation device, Unified Power Quality Conditioner combines the function of the series compensation part and the parallel compensation part. UPQC can compensate for not only harmonics and reactive current by the load, but also supply voltage rise, drop, filcker and other voltage quality problems. It usually consists of a series active power filter, a shunt active power filter and the DC link capacitors. Through the DC link capacitors, the series active power filter and the shunt active power filter are connected in back to back structure [MOHAMMAPI H R, 2009] [Zhu Pengcheng, 2004].

The rapidity and accuracy of tracking control has a great influence on UPQC compensating effect. Now, hysteresis tracking control method is usually used in Unified Power Quality Conditioner(UPQC) because of its quick response, high tracking accuracy and simplicity, but unstable switching frequency causes great switching loss[Wan jinag, 2009]. Furthermore, the interphase interference is very serious in three-phase three-wire system. Based on the shortcomings of the above, a space vector based hysteresis control with fixed switching frequency strategy for UPQC is proposed in this paper, which can not only achieve the fixed frequency, but also overcome the interphase interference. The control strategy is possible and effective by theoretical analysis and simulation.

Hysteresis Control with Fixed Switching Frequency for UPQC

The hysteresis tracking control unit circuit is just as Fig. 1, take phase A for example. The AC voltage is symmetrical, so a neutral point can be got as the reference ground. The neutral point is equipotential to the DC mid-point. The hysteresis band is h . The actual output current i_{ca} is compared with the given current i_{ca}^* , when the current deviation Δi exceeds $\pm h$, the mode of power devices VT_1 and VT_4 controlled by hysteresis controller changes .

Hysteresis tracking control produce the drive signal of UPQC main circuit. On this basis, the corresponding

algorithm is added to ensure the switching frequency fixed. That is the hysteresis control with fixed switching frequency adopted in UPQC.

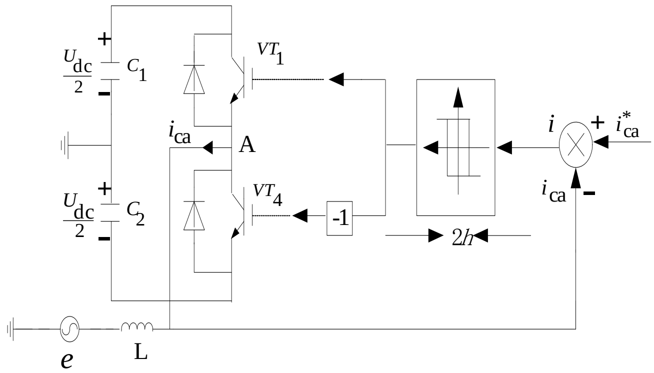


FIG. 1 BLOCK DIAGRAM OF HYSTERESIS TRACKING CONTROL UNIT

According to Fig. 1, the supply voltage instantaneous value equation of phase A is just as follows:

$$e_a + L\frac{di_{ca}}{dt} = u_a \quad (1)$$

The voltage of phase A is u_a . the DC bus mid-point is relative to u_a . u_a equals to $U_{dc}/2$ when VT_1 is on, while $-U_{dc}/2$ when VT_4 is on.

The command current i_{ca}^* is tracked by the output current i_{ca} , and the deviation amplitude can't exceed h .

$$e_a + L\frac{di_{ca}^*}{dt} = u_a^* \quad (2)$$

It is defeined that u_a^* is the reference voltage, now the output current of the inverter will equal to the command current i_{ca}^* . The error current is defined as $\Delta i = i_{ca}^* - i_{ca}$.

Equation (3) can be obtained with (1) and (2):

$$u_a^* - u_a = L\frac{d\Delta i}{dt} \quad (3)$$

The output current controlled by hysteresis tracking is as Fig. 2. Since the switching frequency is high, the reference voltage is considered approximately constant in a switching cycle [Zeng J, 2002]. The rise time t_1, fall time t_2 and a switching cycle time T can be calculated with (3).

Rise time: $$t_1 = \frac{4hL}{U_{dc} - 2u_a^*} \quad (4)$$

Fall time: $$t_2 = \frac{4hL}{U_{dc} + 2u_a^*} \quad (5)$$

A switching cycle time: $$T = t_1 + t_2 = \frac{8hLU_{dc}}{U_{dc}^2 - 4u_a^{*2}} \quad (6)$$

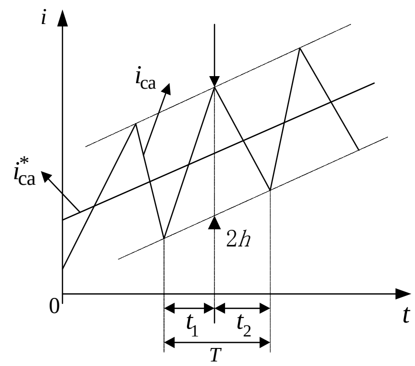


FIG. 2 OUTPUT CURRENT CONTROLLED BY HYSTERESIS TRACKING

The equation (6) is the relationship of the switching period T and the hysteresis band h. The hysteresis band h is fixed in the traditional hysteresis control method, but u_a^* is not constant, so the switching frequency will fluctuate. If the hysteresis band can be adjusted, the equation (6) can be ensured constant. The purpose of fixing switching frequency can be achieved.

The expression of h can be obtained with (2) and (6):

$$h = \frac{U_{dc}^2 - 4(e_a + L\frac{di_{ca}^*}{dt})^2}{8fLU_{dc}} \quad (7)$$

Now, the expected switching frequency f is constant, the hysteresis band h is calculated with (7) to achieve the fixed switching frequency.

Conversion of the Hysteresis Tracking Control

Applying the above-method, the fixed frequency can be acquired in three-phase system, but the interphase interference problem is still not solved. Compared with the space vector, this problem can be solved.

The equivalent circuit of APF based on voltage source is shown in Fig. 3.

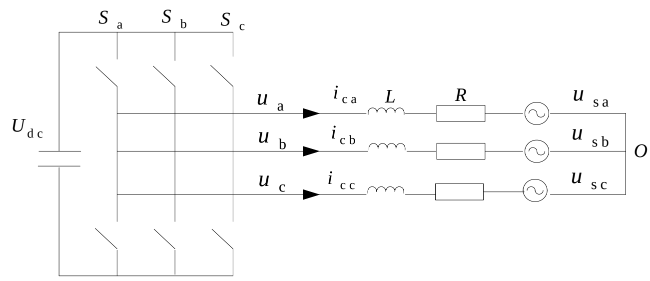


FIG. 3 EQUIVALENT CIRCUIT OF APF

The switching function of arm bridge is S. when the

upper bridge arm is turn on, the lower bridge arm is turn off , S equals to 1, while 0 when the upper bridge arm is turn on, the lower bridge arm is turn off. There are 8 kinds of switch-mode in the Active Power Filter. And therefore, the output voltage vector of the active power filter can be expressed as the corresponding space voltage vector $\boldsymbol{U}_k$ [Guo Ziyong, 2007]:

$$\boldsymbol{U}_k = \begin{cases} \frac{2}{3} U_{dc} e^{\frac{j(k-1)\pi}{3}} & k = 1 \sim 6 \\ 0 & k = 0, 7 \end{cases} \tag{8}$$

After introducing space vector, when the actual output voltage of the inverter tracks the command voltage vector, according to equation (3), it can control rate of change of current error.

The purpose of the UPQC parallel side control system is to make the source current vector $\boldsymbol{i}_s$ to track the source command current vector $\boldsymbol{i}_{sr}$, so the source error vector $\Delta \boldsymbol{i}_s$ is introduced.

$$\Delta \boldsymbol{i}_s = \boldsymbol{i}_{sr} - \boldsymbol{i}_s \tag{9}$$

the supply current are affected by the active filter output current $\boldsymbol{i}_c$ and the load current $\boldsymbol{i}_L$, which $\boldsymbol{i}_c$ is controllable. So the supply current error is limited to the hysteresis band by controlling $\boldsymbol{i}_c$. The current error vector $\Delta \boldsymbol{i} = \boldsymbol{i}_c^* - \boldsymbol{i}_c$ has been defined before, where $\boldsymbol{i}_c^*$ is the command current. Equation (10) is as follow:

$$\begin{aligned} \Delta \boldsymbol{i}_s &= \boldsymbol{i}_{sr} - \boldsymbol{i}_s = (\boldsymbol{i}_c^* + \boldsymbol{i}_L) - (\boldsymbol{i}_c + \boldsymbol{i}_L) \\ &= \boldsymbol{i}_c^* - \boldsymbol{i}_c = \Delta \boldsymbol{i} \end{aligned} \tag{10}$$

Therefore the same vector relationship between $\Delta \boldsymbol{i}_s$ and $\Delta \boldsymbol{i}$ can be acquired.

The hysteresis tracking control of $\boldsymbol{i}_s$ to $\boldsymbol{i}_{sr}$ is converted to that of $\boldsymbol{i}_c$ to $\boldsymbol{i}_c^*$. In a switching cycle , *u** is a constant, so the problem of current control can be changed into that of how to select the right output voltage vector $\boldsymbol{U}_k$. Then $\Delta \boldsymbol{i}$ is limited to a small region and it makes the problem fully simple.

The Control Algorithm for UPQC Parallel Side

Analysis of Control Theory

The theory of space vector based hysteresis control strategy with fixed switching frequency strategy adopted in UPQC parallel is that: the phase current error is considered as the control object and the comparison value is obtained by the hysteresis control with fixed switching frequency. The sign of phase-to-phase current error is used to judged the region of the command voltage vector. The best voltage vector is output by the voltage space vector selection. It can control power devices uniformly. So the command compensation value is tracked by the actual output of the filter, the schematic diagram is shown in Fig. 4.

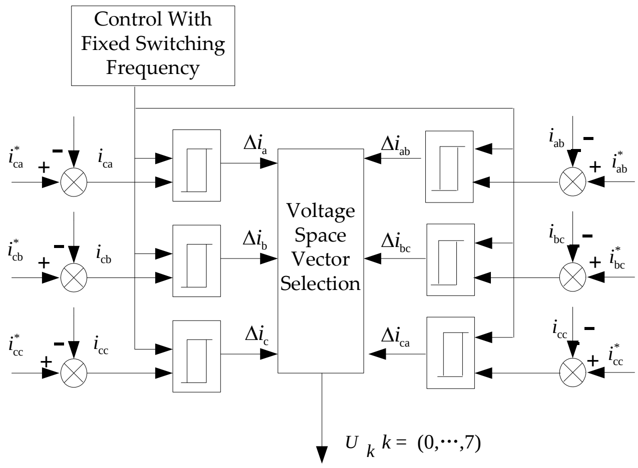


FIG. 4 CONTROL ALGORITHM OF THE PARALLEL SIDE

Region Division of $\boldsymbol{u}^*$、$\Delta \boldsymbol{i}$ and Region Judgment of $\boldsymbol{U}_k$

The vector space is divided into 6 triangle regions, so the area of $\boldsymbol{u}^*$ is also divided into 6 triangle regions, where $\boldsymbol{u}^*$ is the output command voltage vector of the filer which is corresponding to the command compensation current. The regions are marked I~VI in Fig. 5(a). In order to distinguish the positive and negative polarity of $\Delta \boldsymbol{i}_a$、$\Delta \boldsymbol{i}_b$、$\Delta \boldsymbol{i}_c$, the region of $\Delta \boldsymbol{i}$ is also divided into 6 triangle regions. The regions are marked(1)~(6) in Fig. 5(b)[Jiang Junfeng, 2004].

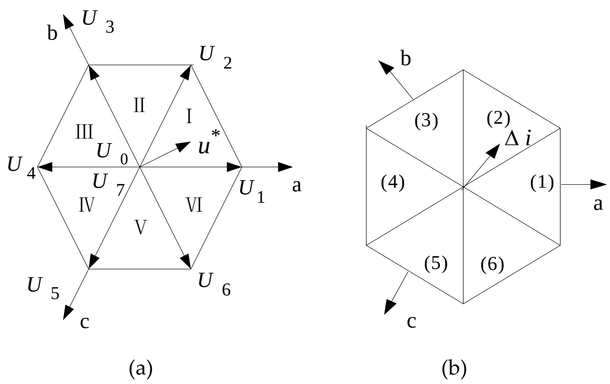


FIG. 5 REGION DIVISION OF $\boldsymbol{u}^*$、$\Delta \boldsymbol{i}$

From (3), The change of $d\Delta \boldsymbol{i}/dt$ is determined by $u^* - u$. when $\boldsymbol{u}^*$ and $\Delta \boldsymbol{i}$ are determined, for the purpose of making sure the direction of $d\Delta \boldsymbol{i}/dt$ is always opposite to $\Delta \boldsymbol{i}$, an appropriate space voltage vector is needed to choice.

When the command voltage vector and the current

error vector are in different regions, The selection situation of the voltage space vector which is satisfying the above conditions , is shown in Table 1[Qu Xueji, 2008].

TAB 1 SELECTION CRITERIA TABLE OF U_k

u^* Region	Δi Region					
	(1)	(2)	(3)	(4)	(5)	(6)
Ⅰ	U_1	U_2	U_2	$U_{0,7}$	$U_{0,7}$	U_1
Ⅱ	U_2	U_2	U_3	U_3	$U_{0,7}$	$U_{0,7}$
Ⅲ	$U_{0,7}$	U_3	U_3	U_4	U_4	$U_{0,7}$
Ⅳ	$U_{0,7}$	$U_{0,7}$	U_4	U_4	U_5	U_5
Ⅴ	U_6	$U_{0,7}$	$U_{0,7}$	U_5	U_5	U_6
Ⅵ	U_1	U_1	$U_{0,7}$	$U_{0,7}$	U_6	U_6

Region Determination of u in Improved Algorithm*

For convenience of description, the three-phase coordinate system "abc" is transformed into a three-phase symmetrical coordinate system "ab—bc—ea".The voltage space vector in the three-phase symmetrical coordinate system is as Fig. 6.

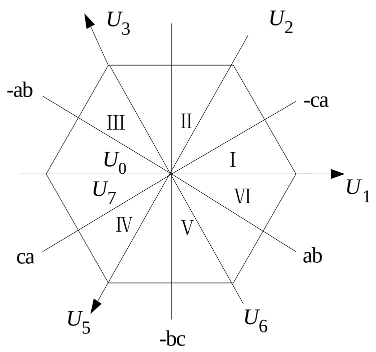


FIG. 6 THREE-PHASE COORDINATE SYSTEM OF AB-BC-CA

It determined the region of command voltage vector by using the sign of phase-to-phase current error. Compared with the traditional judgment method of command voltage vector, it does not need to detect three-phase grid voltage. Furthermore, the algorithm is also optimized. For example, Because of $\Delta i_{ab} = i^*_{ab} - i_{ab}$, when $\Delta i_{ab} < 0$, i_{ab} should be reduced and Δi_{ab} should be approached to 0. For the purposes of reducing i_{ab} , u^*_{ab} should be in the area of $u^*_{ab} < 0$; because of $\Delta i_{bc} = i^*_{bc} - i_{bc}$, when $\Delta i_{bc} < 0$, i_{bc} should be reduced and Δi_{bc} should be approached to 0. For the purposes of reducing i_{bc}, u^*_{bc} should be in the area of $u^*_{bc} < 0$; because of $\Delta i_{ca} = i^*_{ca} - i_{ca}$, when $\Delta i_{ca} > 0$, i_{ca} should be increased and Δi_{bc} should be approached to 0. For the purposes of increasing i_{bc}, u^*_{ca} should be in the area of $u^*_{ca} > 0$. And threrfore, when phase-to-phase current error is $\Delta i_{ab} < 0$, $\Delta i_{bc} < 0$, $\Delta i_{ca} > 0$, the region of command voltage vector is in the area of Ⅳ. The relationship of the command voltage vector and phase-to-phase current error vector is as Tab 2 .

TAB 2 REGION DETERMINATION TABLE OF u^*

u^* Region	Current Error Vector Δi
Ⅰ	$\Delta i_{ab} > 0$, $\Delta i_{bc} > 0$, $\Delta i_{ca} > 0$
Ⅱ	$\Delta i_{ab} < 0$, $\Delta i_{bc} > 0$, $\Delta i_{ca} < 0$
Ⅲ	$\Delta i_{ab} < 0$, $\Delta i_{bc} > 0$, $\Delta i_{ca} > 0$
Ⅳ	$\Delta i_{ab} < 0$, $\Delta i_{bc} < 0$, $\Delta i_{ca} > 0$
Ⅴ	$\Delta i_{ab} > 0$, $\Delta i_{bc} < 0$, $\Delta i_{ca} > 0$
Ⅵ	$\Delta i_{ab} > 0$, $\Delta i_{bc} < 0$, $\Delta i_{ca} < 0$

Region Determination of Δi

Through the polarity of the components on the three axes, the region of Δi is judged. And the output logic of the hysteresis comparator is used to judged the polarities of Δi_a、Δi_b、Δi_c , so the region determination of Δi is shown in Table 3.

TAB 3 REGION DETERMINATION TABLE OF Δi

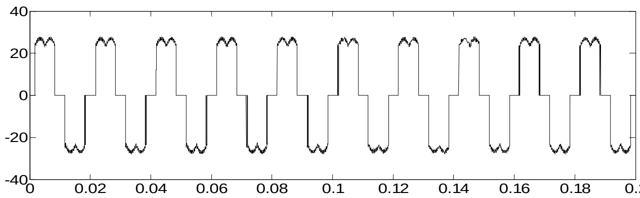
Δi Region	(1)	(2)	(3)	(4)	(5)	(6)
Δi_a	1	1	0	0	0	1
Δi_b	0	1	1	1	0	0
Δi_c	0	0	0	1	1	1

The Control Algorithm for UPQC Serise Side

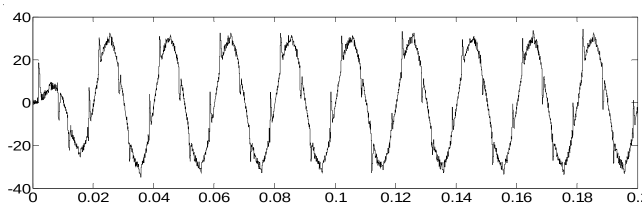
The theory of space vector based hysteresis tracking control strategy with constant switching frequency adopted in UPQC series is that: the phase voltage error is considered as a control object and 3 hysteresis comparators with fixed switching frequency are also used, then the best voltage space vector is output by the voltage space vector selection, according to the corresponding comparing values and the region choice of the command voltage. thus the series actual output voltage of UPQC tracks the command voltage.

Simulation Results and Analysis

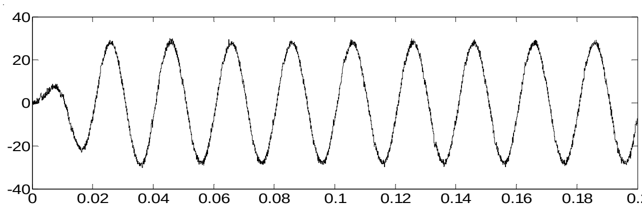
MATLAB/Simulink is adopted as the Power system dynamic simulation software in computer simulation, The model parameters are as follows: supply frequency of three-phase power supply is 50Hz, the valid value of phase voltage is 220V, the ratio of compensation transformer is 1:1, the compensation inductance of series is 5mH, compensation capacitor is 1 μF , the compensation inductance of parallel is 7mH, the filter capacitor is 2.2 μF , PI control is adopted in DC link, the stable voltage value of DC link is 800V, the load is three-phase full-controlled bridge concatenated 2mH inductance and 20 Ω resistance. The simulation time is 0~0.2s. In order to simulate the contaminated power grid, the supply voltage drops 30% from 0.1s to 0.16s during the simulation, meanwhile, 5th harmonic(0.2pu) and 7th harmonic(0.1pu) are added to the grid.



(A) PHASE A LOAD CURRENT BEFORE COMPENSATION

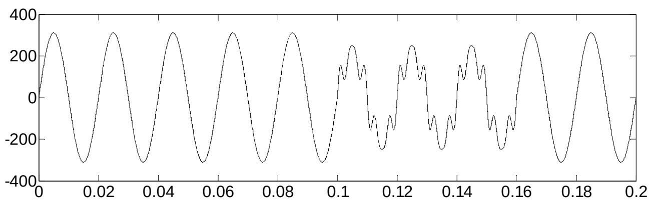


(B) PHASE A SUPPLY CURRENT AFTER COMPENSATION IN TRADITIONAL HYSTERESIS METHOD

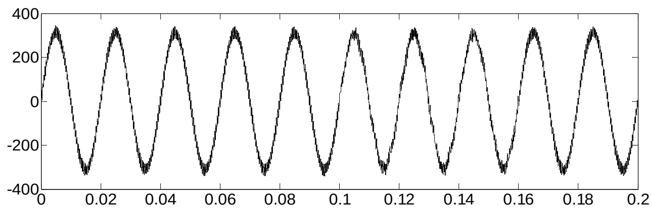


(C) PHASE A SUPPLY CURRENT AFTER COMPENSATION IN THE CONTROL METHOD PROPOSED THIS PAPER

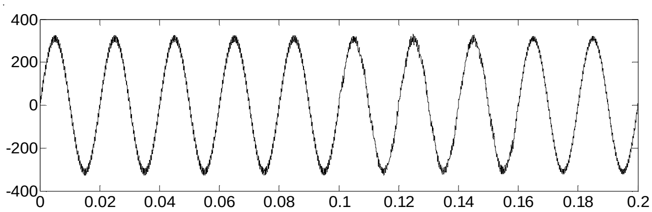
FIG. 7 SIMULATION RESUITS OF THE PARALLEL SIDE



(A) PHASE A SUPPLY VOLTAGE BEFORE COMPENSATION



(B) PHASE A LOAD VOLTAGE AFTER COMPENSATION IN TRADITIONAL HYSTERESIS METHOD



(C) PHASE A LOAD VOLTAGE AFTER COMPENSATION IN THE CONTROL METHOD PROPOSED THIS PAPER

FIG. 8 SIMULATION RESUITS OF THE PARALLEL SIDE

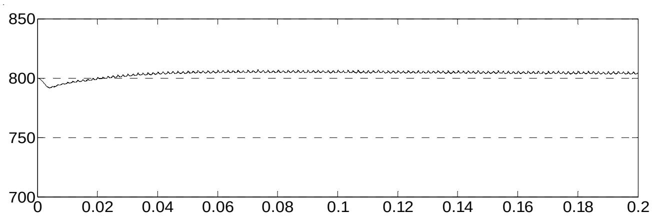


FIG. 9 DC LINK VOLTAGE

The simulation results are shown in Fig. 7, Fig. 8 and Fig. 9. As is shown in Fig. 9, the voltage value of DC link is close to 800V and keeps constant. By the analysis of FFT, the THD of load current is 30.25% before compensation, the THD of supply current reduces to 12.83% in traditional hysteresis control, adopting the control algorithm in this paper, the THD of supply current reduces to 5.37%; the THD of Supply voltage is 31.94% before compensation, the THD of load voltage reduces to 8.63% in traditional hysteresis control, adopting the control algorithm in this paper, the THD of load voltage reduces to 5.76%. As can be seen from the above analysis, the control strategy proposed in this paper is more effective in the performance of improving power quality than the traditional hysteresis control method.

Conclusions

Space vector based hysteresis control strategy with fixed switching frequency for UPQC is proposed in this paper. The improved SVPWM tracking algorithm is adopted in this control strategy. Compared with traditional SVPWM tracking algorithm, the hardware circuit is simplified and the algorithm is optimized. MATLAB/Simulink Simulation results prove this

control strategy can compensate not only the harmonic and reactive current caused by nonlinear loads but also the supply voltage rise and drop. So the power quality gets improved. Furthermore, this control strategy can overcome the shortcoming of interphase interference and the problem of switching loss.

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